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DYNAMIC BEHAVIOR OF FIBROUS FILTERS
DURING
COLLECTION OF SUBMICROMETER
AEROSOLS:
A DISPERSION MODEL

Final Report

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and
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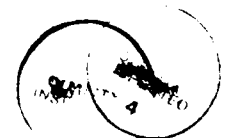
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13. ABSTRACT (Maximum 200 words) A novel fundamental theory of the dynamic behavior of fibrous filters for aerosol collection is proposed. The theory is based upon an explicit and systematic procedure for calculating the filter efficiency η and for quantitatively describing the filter microstructure, both of which change continuously during filter operation as aerosol particles deposit on the fibers. This theory is free of any of the usual ad hoc assumptions, including the artificial concept of single-fiber efficiency η_0 , explicit or implicit theories. Upon viewing the filter bed as a continuum, the aerosol transport and deposition processes at this coarse-scale level of description are characterized by three fundamental 'global' phenomenological coefficients: (i) the mean aerosol velocity vector \bar{U} ; (ii) dispersivity dyadic \bar{D} ; and (iii) mean volumetric aerosol deposition-rate coefficient \bar{K} . Whereas for clean homogeneous filters these phenomenological coefficients are constants, continuous aerosol deposition on the fiber surfaces causes them to vary with both time t and position \bar{r} within the filter bed. The filtration efficiency may be rationally expressed explicitly in terms of these three physically realistic, experimentally accessible quantities. The scheme proposed herein will serve to calculate \bar{U} , \bar{D} and \bar{K} , followed by subsequent use of these quantities to characterize the dynamic, i.e. temporal, filter behavior. An outline of the importance of the proposed theoretical research is presented that addresses the following items: (i) rigorous and systematic study of the effects of the various filtration operating parameters and aerosol properties upon the dynamic behavior of fibrous filters; (ii) establishment of the limitations of existing filtration theory in the light of these new theoretical developments; (iii) interpretation of experimental data.				
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This report* summarizes activities performed during the period 1 October 1987-31 December 1990.

STATEMENT OF THE PROBLEM STUDIED

Development of the dispersion/reaction model for collection of submicrometer aerosol particles in porous filters. Study of coarse-scale aerosol transport mechanics and particle deposition rates within the filter bed. Investigation of the dynamics of transport and deposition processes of fine particles within fibrous filters.

SUMMARY OF THE MOST IMPORTANT RESULTS

1. Development of a rigorous analytical theory of transport and deposition of aerosol particles in spatially periodic models of porous fibrous and granular filters. This theory constitutes a significant advancement in understanding and modelling of aerosol transport and collection processes in porous beds, as well as in the interpretation of available experimental data and planning of further experiments.
2. Development of a numerical finite-element model for computation of coarse-scale aerosol transport properties, namely the mean aerosol velocity vector, dispersivity dyadic, and effective volumetric aerosol deposition-rate coefficient. These data were used for direct calculation of the effective aerosol filtration length and filtration efficiency without utilizing the *ad hoc* concept of "single-element efficiency" employed in classical filtration theory.
3. Numerical study of the fluid velocity field within spatially periodic porous fibrous beds. Investigation of the effects of the microscale Reynolds number, filter void fraction, bed microstructure, and bed polydispersity upon the pressure drop across the filter.
4. Calculation of the coarse-scale aerosol transport and deposition properties and characteristic aerosol filtration lengths within spatially periodic lattice models of fibrous filters. Numerical study of the effects of characteristic microscale Peclet number and interception parameter, bed packing arrangement, and porosity upon the characteristic aerosol filtration length. Investigation of influences of diffusional and interceptional aerosol collection mechanisms upon aerosol collection rates. The results obtained were in accord with available experimental

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- data, while the results of competitive models (derived from classical filtration theory) exhibited poor agreement.
5. Investigation of the roles of short-range dispersion forces in the deposition and accumulation of aerosol particles upon solid collector surfaces. Development of boundary conditions for the aerosol concentration field on the fiber surface, required for investigating the dynamics of aerosol collection and accumulation within the filter bed.
 6. Numerical investigation of the transport and deposition of chemically reactive aerosol particles in fibrous filters. Study of the effect of the microscale aerosol reactivity upon the characteristic filtration length. Modelling of the influence of particle re-entrainment from the fiber collector surfaces (usually occurring during the process of filter contamination) upon the net aerosol collection rate.
 7. Theoretical calculation of the coarse-scale aerosol transport coefficients for aerosol particles undergoing adsorption/reaction processes on the surfaces of fibrous collectors. Investigation of the effects of the aerosol surface-excess reactivity and fiber adsorptive properties upon the aerosol's coarse-scale transport mechanisms and collection rates.

ADDITIONAL ACHIEVEMENTS, WHICH WERE NOT ORIGINALLY PLANNED IN THE PROPOSED PROJECT

1. Investigation of electrostatically enhanced aerosol transport and deposition processes from turbulent flows in electrostatic precipitators.
2. Study of aerosol particle sedimentation in unbounded cellular flows.
3. Investigation of low Reynolds number motion of an aerosol particle in the vicinity of a curved collector surface, occurring within a spatially periodic filter bed.
4. Feasibility study of the control of aerosol particle motion in a closed environment by application of time-periodic external (e.g. electrostatic, magnetic, etc.) forces transverse to the air flow stream.
5. General theory of the convective-diffusive transport of aerosol particles in tube and channel flows, as well as in spatially periodic models of porous media.

LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED UNDER ARO SPONSORSHIP DURING THIS PERIOD, INCLUDING JOURNAL REFERENCES

Journal Publications

- (1) A. Falade and H. Brenner, "First order wall curvature effects upon the Stokes resistance of a spherical particle moving in close proximity to a solid wall," *J. Fluid Mech.* **193**, 533-568 (1988).

- (2) M. Shapiro, A. Oron and C. Gutfinger, "A dispersion model for electrostatic precipitation of fine particles from turbulent flows," *PhysicoChem. Hydrodyn.* **10**, 471-491 (1988).
- (3) S.R. Dungan and H. Brenner, "Sedimentation and dispersion of nonneutrally buoyant Brownian particles in cellular flows simulating local fluid agitation," *Phys. Rev. A* **38**, 3601-3608 (1988).
- (4) M. Shapiro, A. Oron and C. Gutfinger, "Electrostatic precipitation of charged particles from turbulent flows between co-axial cylinders," *J. Colloid Interface Sci.* **127**, 401-416 (1989).
- (5) L.C. Nitsche and H. Brenner, "Eulerian kinematics of flow through spatially periodic models of porous media," *Arch. Rational Mech. Anal.* **107**, 225-292 (1989).
- (6) I. Frankel and H. Brenner, "On the foundations of generalized Taylor dispersion theory," *J. Fluid Mech.* **204**, 97-119 (1989).
- (7) S.R. Dungan and H. Brenner, "Force and torque on a body in an unbounded Stokes flow expressed explicitly in terms of respective quadratures of the pressure and vorticity fields," *Chem. Eng. Commun.* **82**, 103-110 (1989).
- (8) M. Shapiro and H. Brenner, "Dispersion and deposition of aerosol particles in porous filters," *J. Aerosol Sci.* **20**, 951-954 (1989).
- (9) M. Shapiro and H. Brenner, "Dispersion/reaction model of aerosol filtration by porous filters," *J. Aerosol Sci.* **21**, 97-125 (1990).
- (10) M. Shapiro, H. Brenner and D.C. Guell, "Accumulation and transport of Brownian particles at solid surfaces: Aerosol and hydrosol deposition processes," *J. Colloid Interface Sci.* **136**, 552-573 (1990).
- (11) D.A. Edwards, M. Shapiro, P. Bar-Yoseph and M. Shapira, "The influence of Reynolds number upon the apparent permeability of spatially-periodic arrays of cylinders," *Phys. Fluids A* **2**, 45-55 (1990).
- (12) S.R. Dungan, M. Shapiro and H. Brenner, "Convective-diffusive-reactive Taylor dispersion processes in particulate multiphase systems," *Proc. Roy. Soc. London A* **429**, 639-671 (1990).
- (13) M. Shapiro and H. Brenner, "Taylor dispersion in the presence of time-periodic convection phenomena. Part I. Local-space periodicity," *Phys. Fluids A* **2**, 1731-1743 (1990).
- (14) M. Shapiro and H. Brenner, "Taylor dispersion in the presence of time-periodic convection phenomena. Part II. Transport of transversely oscillating Brownian particles in a plane Poiseuille flow," *Phys. Fluids A* **2**, 1744-1753 (1990).
- (15) L.C. Nitsche and H. Brenner, "Hydrodynamics of particulate motion in sinusoidal pores via a singularity method," *AIChE Jour.* **36**, 1403-1419 (1990).
- (16) H. Brenner, "Macrotransport Processes," *Langmuir* **6**, 1715-1724 (1990).
- (17) M. Shapiro, I.J. Kettner and H. Brenner, "Dispersion model for interceptional and diffusional collection of fine particles in fibrous beds. A comparison with experiments," *J. Aerosol Sci.* **21**, S713-S718 (1990).

- (18) H. Brenner, "Macrotransport processes: Brownian tracers as stochastic averagers in effective-medium theories of heterogeneous media," *J. Statistical Phys.* **62**, 1095-1119 (1991).
- (19) D.A. Edwards, M. Shapiro, H. Brenner and M. Shapira, "Dispersion of inert solutes in spatially periodic, two-dimensional model porous media," *Transp. Porous Media* (revision accepted for publication, 1991).
- (20) M. Shapiro, I.J. Kettner and H. Brenner, "Transport mechanics and collection of submicrometer particles in fibrous filters," *J. Aerosol Sci.* (submitted, 1991).

Chapters Published in Books

- (1) H. Brenner, "Macrotransport Processes," in *Eighteen Years of Colloid and Surface Chemistry, The Kendall Award 1973-1990*, (K.J. Mysels and T. Fort, Jr., Eds.), American Chemical Society, Washington, D.C. (in press, 1991).

Papers Published in Proceedings of Scientific Conferences

- (1) M. Shapiro and H. Brenner, "Diffusion reaction model of aerosol filtration by fibrous filters," *Proc. of the 23rd Israel Conference on Mechanical Engineering*, Technion-Israel Institute of Technology, Haifa, Israel (May 21-22, 1990), 4 pp.
- (2) M. Shapiro and H. Brenner, "Dispersion/reaction model of aerosol filtration by porous filters," *Proceedings of the 1989 CRDEC Scientific Conference on Obscuration and Aerosol Research*, (E.H. Engquist and D.A. Clark, Eds.), pp. 15-24, Report No. CRDEC-SP-026, Battelle-Edgewood Operations, Edgewood, Maryland (1990).
- (3) M. Shapiro and H. Brenner, "Interceptional and diffusional collection of fine particles in fibrous beds. A dispersion model," *Proceedings of the 1990 CRDEC Scientific Conference on Obscuration and Aerosol Research*, (R.H. Kohl, Ed.), (June, 1990), 8 pp.
- (4) M. Shapiro, I.J. Kettner and H. Brenner, "Interceptional and diffusional filtration of fine particles in fibrous filters," *Proc. of the European Aerosol Conference*, Zurich, Switzerland, (October 1-5, 1990), 4 pp..
- (5) M. Shapiro, I.J. Kettner and H. Brenner, "Interceptional and diffusional collection of fine particles in fibrous beds. A dispersion model," in *Aerosol Science, Industry, Health and Environment*, Proceedings of the 3rd International Aerosol Conference, Kyoto, Japan (S. Masuda and K. Takahashi, Eds.), Pergamon Press, Vol. 2, pp. 706-709 (1990).

Theses

- (1) Stephanie R. Dungan, "Low Reynolds number flow and dispersion processes in fluid-particle systems." M.Sc. Thesis in Chemical Engineering. Massachusetts Institute of Technology (January, 1988).
- (2) Ludwig C. Nitsche, "Multiphase flow through spatially periodic porous media," Ph.D. Thesis in Chemical Engineering. Massachusetts Institute of Technology (May, 1989).

- (3) Gretchen M. Mavrovouniotis, "Transport properties of interfaces containing surface active substances: A micromechanical investigation," Ph.D. Thesis in Chemical Engineering. Massachusetts Institute of Technology (August, 1989).
- (4) David C. Guell, "The physical mechanism of osmosis and osmotic pressure: A hydrodynamic theory for calculating the osmotic reflection coefficient," Ph.D. Thesis in Chemical Engineering. Massachusetts Institute of Technology (November, 1990).

SCIENTIFIC PERSONNEL EMPLOYED ON THIS PROJECT, AND ADVANCED DEGREES AWARDED

Professor Howard Brenner (Principal Investigator).
Dr. Michael Shapiro (Visiting Scientist).
Dr. Itzhak Frankel (Visiting Scientist).
Dr. Shimon Haber (Visiting Scientist).
David C. Guell (Ph.D. awarded, November 20, 1990).
Ludwig C. Nitsche (Ph.D. awarded, May 25, 1989).
Stephanie R. Dungan (M.Sc. awarded, August, 1987).
Gretchen M. Mavrovouniotis (Ph.D. awarded, August 7, 1989).
Alejandro Mendoza-Blanco (Ph.D. student, currently in progress).
Michael Kezirian (Ph.D. student, currently in progress).

REPORT OF INVENTIONS

None